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Geographic Information System Application for Prospecting the Sandstone-type Uranium Deposit in the Melawi Region, West Kalimantan, Indonesia

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Abstract

The Melawi region in Indonesia has been identified as a metamorphic-hosted uranium deposit. The occurrence of sedimentary formations in the downstream area suggests the potential for sandstone-type uranium deposits. Previous studies have concentrated on metamorphic-hosted mineralization, resulting in limited exploration of the sedimentary rocks. Geographic Information System (GIS) technology offers valuable support for mineral prospectivity analysis, including uranium exploration. Among various techniques, fuzzy logic has been demonstrated to be effective in generating prospectivity maps to guide uranium resource development. This research aims to develop a prospectivity map for a sandstone-type uranium deposit in the Melawi region. A GIS-based analysis is performed using available spatial datasets, including geological maps, digital elevation models, and uranium occurrences in Melawi. These datasets served as input for constructing a fuzzy logic model based on the genetic model of sandstone-type uranium deposits. The datasets were reclassified, assigned suitability scores, and operated within a fuzzy logic framework to generate a prospectivity map. The results indicate that 36.64% of the Melawi area is high prospectivity zones, 25.34% is medium prospectivity zones, and 38.02% is the low prospectivity zones. The northern part of Melawi exhibits the most favourability for sandstone-hosted uranium mineralization. This study demonstrates fuzzy logic as a practical tool to delineate the favourable area of a sandstone-type uranium deposit in Melawi. Nevertheless, incorporating more diverse spatial datasets and implementing systematic field validation is necessary to locate uranium deposits accurately.

Keywords:
Melawi, GIS, fuzzy logic, mineral prospectivity, sandstone-type uranium

1. Introduction

As the global demand for clean and sustainable energy rises, nuclear power is increasingly seen as a reliable low-carbon solution (**Karakosta et al., 2013; Yue et al., 2022**). Indonesia has included nuclear energy in its national energy strategy, with plans to develop nuclear power plants (NPP) in the coming decades to ensure long-term energy security and reduce dependence on fossil fuels (**Permana et al., 2022**). This policy direction highlights the importance of identifying domestic uranium resources to support future nuclear fuel needs. Indonesia hosts several types of uranium deposits, including metamorphic-type in West Kalimantan (**Adimedha et al., 2024; Ciputra et al., 2022; Ngadenin et al., 2017**), alkaline volcanic-related-type in West Sulawesi (**Rosianna et al., 2020, 2023; Said et al., 2017; Sukadana et al., 2016**), placer-type in Bangka Belitung (**Ngadenin et al., 2014; Syaeful et al., 2021**), and sandstone-type in North Sumatra (**Ciputra et al., 2019a; Subandrio et al., 2010; Sukadana & Syaeful, 2016**). Despite this geological potential, uranium deposits remain difficult to locate due to economic, environmental, and geological challenges. Therefore, a method capable of integrating and analysing diverse geoscientific data is essential to improve the effectiveness and efficiency of uranium exploration in Indonesia.

In recent years, Geographic Information Systems (GIS) have emerged as powerful tools for mineral exploration, offering spatial analysis capabilities that allow integration of multiple geoscientific datasets (**Carranza, 2008; Porwal & Kreuzer, 2010; Yousefi et al., 2019**). When combined with fuzzy logic modelling, GIS enables the quantification of expert geological knowledge and the handling of uncertainty in data, which is particularly relevant in early-stage uranium exploration. Although recent advancements in machine learning and deep learning have shown promise in mineral prospectivity modelling (**Brandmeier et al., 2020; Kong et al.,**

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2024; Li et al., 2024; Senanayake et al., 2023; Sun et al., 2024), these data-driven methods typically require a large number of known mineral occurrences and high-quality, high-density datasets to establish reliable statistical relationships. In contrast, the fuzzy logic approach is knowledge-driven and therefore well-suited to data-sparse environments. Fuzzy logic also allows expert judgment and qualitative geological reasoning to be formally expressed in a quantitative framework. This characteristic provides a key advantage over purely statistical or training-based algorithms, which may fail to capture subtle geological reasoning when a sample size is small or uncertain (**Bierlein & Bruce, 2018**). GIS-fuzzy logic approaches have proven to be effective in reducing exploration risks and improving targeting efficiency by producing spatially explicit prospectivity maps (**Carranza, 2008**). Fuzzy logic models allow qualitative geological concepts, such as favourability based on lithology, topography, or hydrogeological conditions, to be translated into quantitative inputs (**Berthold, 1999**). This method is particularly suitable for sandstone-type uranium deposits, which require the presence and interplay of three primary geological components: (1) a uranium source, commonly felsic igneous or metamorphic rocks enriched in uranium; (2) transport pathways, typically through permeable sandstones and aided by groundwater circulation; and (3) trap environments, such as reducing facies within sandstones, often interbedded with carbonaceous or pyritic material, that allow uranium precipitation and accumulation (**Bruneton & Cuney, 2016**). The use of GIS-fuzzy logic for uranium exploration has already demonstrated encouraging results (**Bierlein & Bruce, 2018; Kreuzer et al., 2010**). In North Sumatra, Indonesia, prospectivity maps developed using fuzzy logic successfully delineated areas with high favourability that were later confirmed by the presence of uranium mineralization (**Ciputra et al., 2019b**). However, as with any predictive model, the outputs must be validated through field investigations and supporting geophysical and geochemical techniques to ensure accuracy and reliability.

Despite Indonesia's favourable geological setting and the documented presence of various uranium deposit types, systematic exploration remains at a relatively early stage. One of the major challenges is the absence of integrated, data-driven approaches that can effectively address the inherent geological complexity and data uncertainty characteristic of Indonesia. The Melawi region in West Kalimantan represents a geologically promising but largely underexplored area for uranium mineralization. The regional geology is characterized by Pre-Tertiary granitoid intrusions, metamorphic basement rocks, and extensive Tertiary sedimentary sequences, including sandstone formations (**Amiruddin & Trail, 1993**). Granitoids and metamorphic rocks in the southern part of Melawi could represent viable uranium sources **(Syaeful et al., 2021**). Moreover, metamorphic rocks in the southern part of Melawi have been extensively explored for uranium mineralization (**Ciputra et al., 2020, 2022; Farrenzo et al., 2023; Muhammad et al., 2019; Sukadana et al., 2024; Syaeful et al., 2021**). This fact is supported by the potential uranium traps of sandstone in the northern part of Melawi, particularly due to the presence of thin coal seams and mudstones that could serve as reductive agents (**Cakrabuana et al., 2021a; Indrastomo et al., 2024**). Despite these favourable geological conditions, exploration focusing on sandstone-type uranium deposits in this area remains limited to date. The lack of quantitative spatial assessment integrating these components (source, transport, and trap) has hindered the ability to delineate prospective zones and prioritize exploration targets.

To address these limitations, this study applies a GIS-based fuzzy logic approach to develop a prospectivity map for sandstone-type uranium deposits in the Melawi region. This research provides spatially integrated assessment of sandstone-type uranium potential in West Kalimantan, integrating key geological parameters related to uranium source, transport pathways, and trap mechanisms within mineralization framework. This research demonstrates how integrated spatial analysis can enhance exploration target delineation in data-sparse regions. The proposed methodology provides a replicable framework that can be adapted to other sedimentary basins across Indonesia and Southeast Asia. The resulting prospectivity map is expected to serve as a strategic guide for further exploration activities and contribute to a broader understanding of Indonesia's uranium resource potential.

1.1. Geological Background

1.1.1. Sandstone-type Uranium Deposit

Sandstone-type uranium deposits were formed in diagenetic–epigenetic and low-temperature origin (**Bruneton & Cuney, 2016; IAEA, 2009**). An essential element that controls the formation of sandstone-type uranium deposits consists of source rock, permeability, groundwater chemistry, depositional environment, the presence of adsorptive/reducing agents, and an arid to semi-arid climate (**Bruneton & Cuney, 2016; IAEA, 2009**). Lithologies that are considered to be potential uranium source rocks are felsic volcanic, crystalline terrains, or other lithologies with sufficient amounts of uranium content. The favourable area for a uranium source is exposed granitoid rocks, as it is more likely to release uranium during weathering (**Dahlkamp, 2009**). The oxygenated surface and groundwaters could act as leaching and transporting agents for uranium. The uranium transport is also controlled by topographic relief and the permeability of rocks. Then uranium would be trapped in medium to coarse-grained sandstone with the presence of reducing agents such as carbonaceous materials, sulphides, or ferromagnesian minerals. The depositional environments of

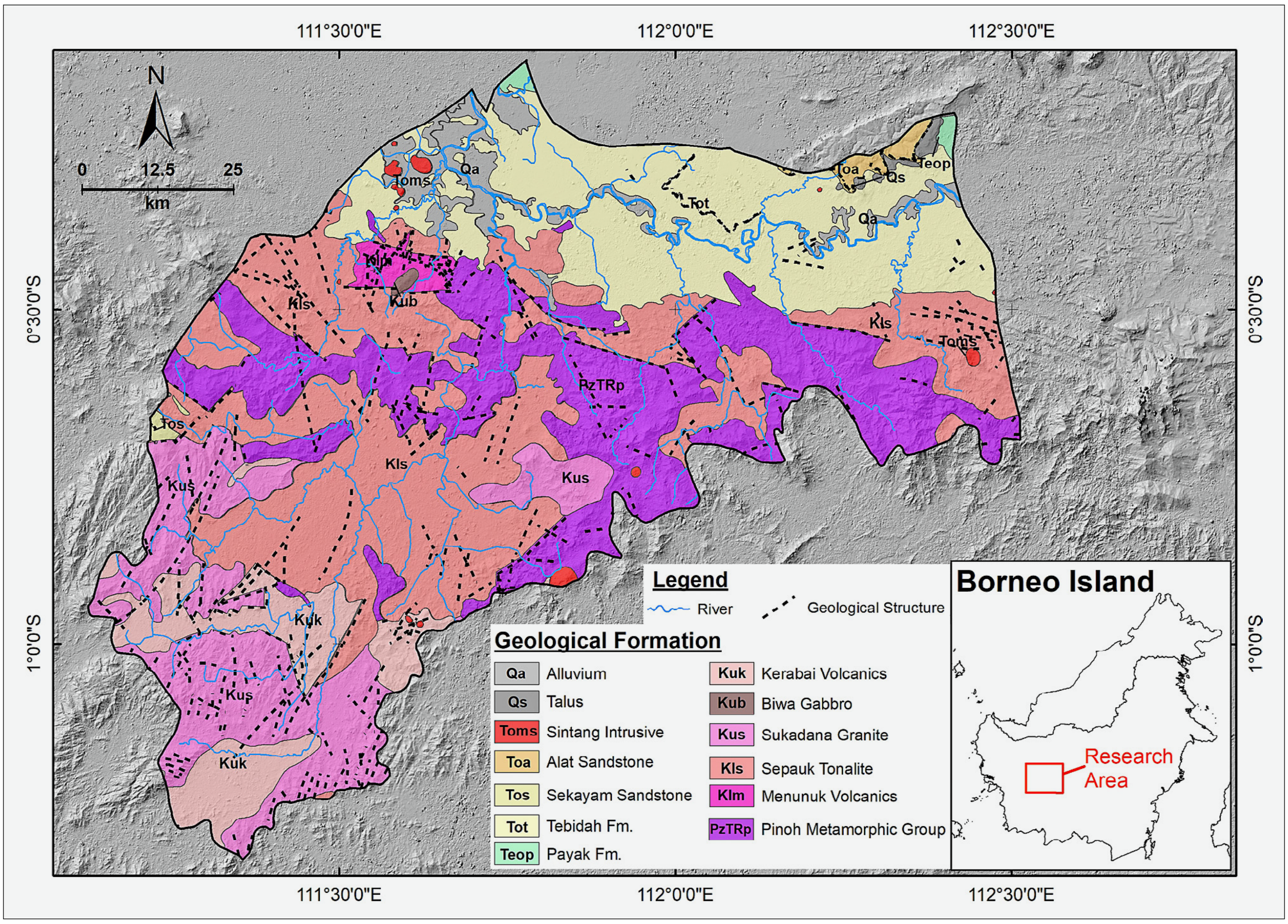

Figure 1. Geological map of Melawi, West Kalimantan, Indonesia (modified from Amiruddin & Trail (1993)).

sandstone-type uranium deposits are fluvial to lacustrine in intracratonic to epicratonic sedimentary basins (**Bruneton & Cuney, 2016; IAEA, 2009**).

1.1.2. Geology of the Melawi Region

The Melawi region lies within the Melawi basin (**Sutjipto, 1991**) and is part of the Northern Zone of Schwaner Mountains (**Breitfeld et al., 2020; Hennig et al., 2017**), where the basement of the Melawi basin is exposed. The Melawi basin, a Paleogene-aged sedimentary basin located in western Kalimantan, is bounded by the Semitau Plateau to the north and the Schwaner Mountains to the south (**Sutjipto, 1991**). The basement rocks of this basin consist of Early Cretaceous Pinoh Metamorphics, composed of quartz-muscovite schist, phyllite, hornfels, tuff, and quartzite (**Amiruddin & Trail, 1993**). These metamorphic rocks were later intruded by several Upper Cretaceous plutonic bodies, including Sukadana Granite, Sepauk Tonalite, and Biwa Gabbro (**Breitfeld et al., 2020; Davies et al., 2014; Hennig et al., 2017**).

The Sepauk tonalite comprises tonalite and light gray hornblende-biotite granodiorite, with occurrences of diorite, granite, monzodiorite, and quartz diorite. The Sukadana Granite is predominantly composed of alkaline feldspar granite and monzogranite, while the Biwa Gabbro consists mainly of Olivine Gabbro. The Pinoh Metamorphic is overlaid by Upper Cretaceous Menunuk Volcanics (tuff, siltstone, and mudstone) and the Kerabai Volcanic (andesite, basalt, and dacite). The sedimentary sequence of the Melawi region begins with the Late Eocene – Early Oligocene Payak Formation, consisting of tuffaceous quartz wacke interbedded with grey mudstone and siltstone, which are notably rich in fossils (**Badaruddin et al., 2018; Sutjipto, 1991**). This formation is overlaid by the Early Oligocene Tebidah Formation is composed of lithic arenite interbedded with mudstone and thin coal seams (**Badaruddin et al., 2018; Sutjipto, 1991**). Above this lies the Early Oligocene Sekayam Sandstone, comprising massive to thick-bedded sandstone with mudstone interbeds (**Badaruddin et al., 2018; Sutjipto, 1991**), followed by the Alat Sandstone, which includes thick-bedded sandstones and conglomerates (**Amiruddin & Trail, 1993**). These sedimentary formations were later intruded by the Upper Oligocene–Lower Miocene Sintang Intrusive Suite, consisting of andesite, dacite, rhyolite, quartz diorite, and granodiorite. Quaternary deposits of talus and alluvium are the youngest geological units in the region (**Amiruddin & Trail, 1993**). The geological framework of the Melawi region is illustrated in **Figure 1.**

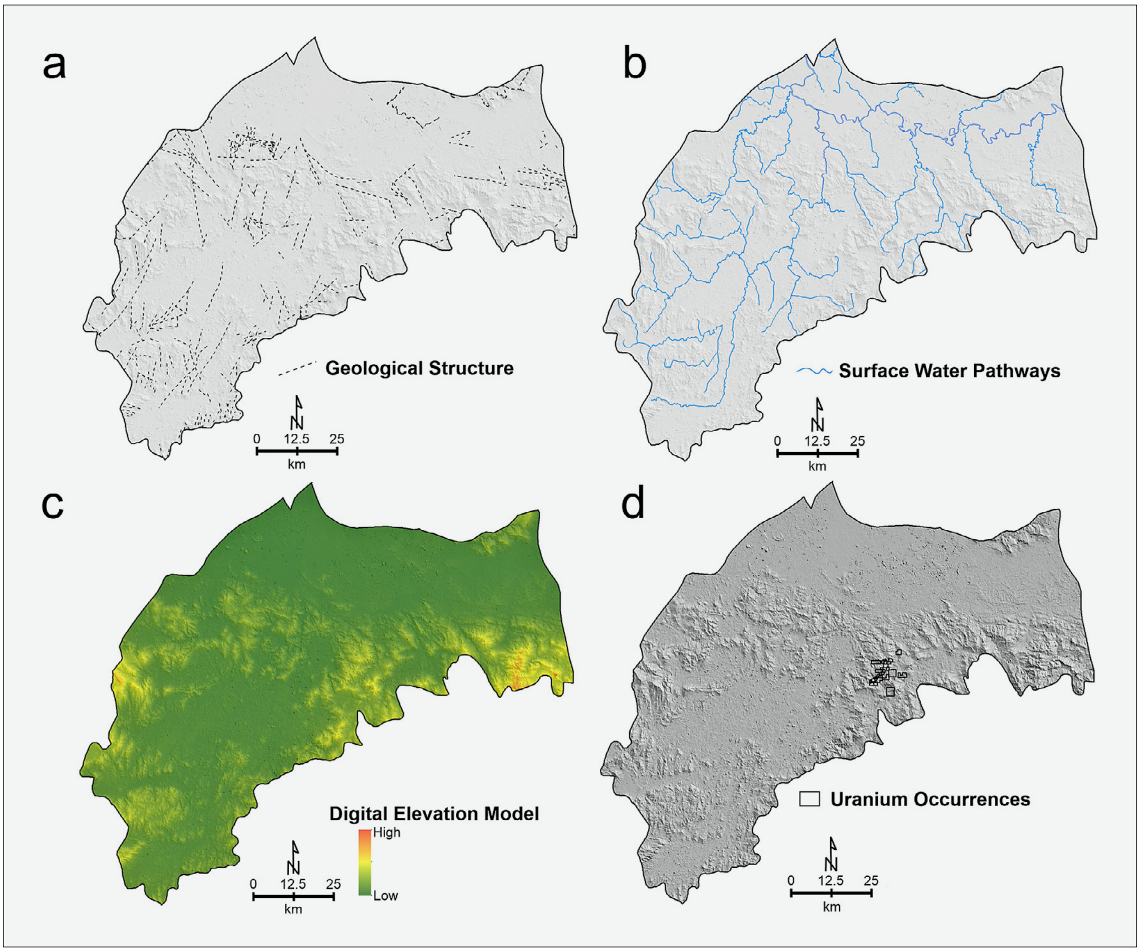

Figure 2. Illustration of spatial datasets used as input in fuzzy logic (a) geological structure (after Amiruddin & Trail (1993)), (b) surface water pathways (after Badan Informasi Geopasial (2017)), (c) digital elevation model (after United States Geological Survey), (d) uranium mineralization occurences (after Ciputra et al. (2022)).

Uranium mineralization within the Melawi region has been documented in the Kalan area, located upstream of the Kalan River and situated within the Pinoh Metamorphic Complex. The metamorphic rock has been intruded by granitoid bodies, particularly the Sepauk Tonalite and Sukadana Granite (**Ciputra et al., 2022; Tjokrokardono et al., 2004**). Uranium occurs in low-grade metamorphic rocks, especially metasiltstones and metapelites, which are characterized by clay-rich mineral assemblages (**Farrenzo et al., 2023; Syaeful et al., 2021**). The inferred uranium resource in the Kalan area is estimated at approximately 2470 tonnes of uranium (tU) (**Syaeful et al., 2021**). The uranium mineralization is associated with a diverse suite of uranium-bearing minerals, including uraninite, brannerite, davidite, gummite, and high-uranium monazite (**Adimedha et al., 2024; Syaeful et al., 2021; Tjokrokardono et al., 2004**). Faults, structural openings, and tectonic breccias control the mineralization. Additionally, uranium enrichment is locally concentrated along schistosity planes within the host rocks, reflecting the structural and lithological control on mineral distribution (**Tjokrokardono et al., 2004**).

Table 1. Spatial datasets used in GIS-based prospectivity mapping for a sandstone-type uranium deposit.

Spatial Datasets	Criteria
Regional Geology (**Amiruddin & Trail, 1993**)	Lithology reclassification as a uranium source
	Geological structure as fluid media
	Sandstone as a uranium trap
	Permeability reclassification as fluid transport media
Surface water pathways (**Badan Informasi Geopasial, 2017**)	Surface water pathways as transport media
Digital Elevation Model (ASTER GTM2) **(United States Geological Survey, n.d.)**	Local lows generation
Uranium Occurrences (**Ciputra et al., 2022**)	Uranium potential areas in the Melawi region

2. Methods

Studies in fuzzy logic methods for mineral prospectivity mapping have been conducted not only for uranium, but other mineral deposits, for example, iron-copper-gold (**Nykänen et al., 2008**), polymetallic mineralization (**Arjmand Lary et al., 2024**), and a hydrothermal gold deposit (**Abdelkareem & Al-Arifi, 2021**). These studies commonly integrate multiple spatial datasets such as regional geology, geochemistry, and satellite imagery. The selection of parameters and analytical techniques for uranium prospectivity mapping using GIS generally follows established frameworks (**Bierlein & Bruce, 2018; Ciputra et al., 2019b**). which outline typical data sources and suitable spatial analysis methods.

In this research, the approach was adapted to align with the geological characteristics of the Melawi region and the sandstone-type uranium model, with parameter selection reflecting the datasets available at the regional scale. Accordingly, the analysis emphasizes geological, geomorphological, and structural information relevant to the mineralization framework. The datasets incorporated into this study are described in detail below.

2.1. Spatial Data

The spatial datasets utilized in this research are selected based on key geological and environmental components relevant to the formation of sandstone-type uranium deposits. The spatial datasets are sourced from publicly available online data or digitized from existing regional maps. The spatial datasets include a 1:250,000 scale regional geological map, incorporating regional geology (see **Figure 1**) and geological structure (see **Figure 2a**), a surface water drainage map (see **Figure 2b**), a digital elevation model (DEM) (see **Figure 2c**), and a map of known uranium occurrence within the Melawi region (see **Figure 2d**). Each dataset plays a specific role in supporting the modelling and analysis of sandstone-type uranium prospectivity, which is described in **Table 1**.

2.2. Predictor Map Generation

Using the collected spatial data, a series of predictor maps is developed, each representing a key component of the genetic model for uranium mineralization. These maps are generated using GIS software, employing the UTM zone 49S coordinate system and WGS 1984 datum. The predictor maps are generated by reclassifying and processing spatial criteria derived from the datasets, which correspond to geological and environmental factors with sandstone-type uranium deposits. The resulting predictor maps include the following:

2.2.1. 'Source' map

The uranium source predictor map ('Source') was generated using surface geological data from the Melawi region. Rock units are reclassified into favourable uranium sources (granitoid igneous rocks) and less favourable sources (sedimentary, volcanic, and alluvial rocks). Furthermore, granitoid rocks are categorized based on their age, with older intrusions considered more favorable for uranium generation than the younger ones due to their longer exposure to weathering. A special case for the Melawi region is the Pinoh Metamorphic Complex, which hosts known uranium occurrences, particularly in the Kalan area (**Ngadenin et al., 2017**). The metamorphic rocks in this area are scored slightly lower with granitoid sources.

The genetic model of sandstone-type uranium mineralization states that potential sources of uranium are areas close to granitoid rocks because they are more likely to release uranium during the weathering process. The further from the granitoid source, the less favorable it becomes. Therefore, a five-level distance buffer ranging from 100 m to 5 km that accommodates potential uranium sources is applied around granitoid and metamorphic rocks (see **Figure 3a-c**). These buffer distances are considered reasonable, rational, and realistic given the scale of the research area, though they can be modified based on future adjustments in mapping resolution.

In addition to crystalline sources, sedimentary rocks themselves may also serve as minor uranium sources, as they can contribute to uranium enrichment within the sandstone host, albeit to a lesser extent. Therefore, lithological classification maps are also integrated into the model to accommodate the potential uranium ontribution from sedimentary or other rock types (see **Figure 3d**).

2.2.2. 'Transport' map

The critical factor influencing the mobility and transport of uranium in sandstone-type deposits is groundwater flow through porous and permeable media. These media are typically associated with specific geological structures and lithological units, which provide pathways for fluid migration. Surface water patterns are also an important component in uranium transport. In addition to subsurface flow, surface water systems, such as rivers and drainage networks, also play a significant role in uranium mobilization, particularly in facilitating the redistribution of dissolved uranium. Although the river networks reflect the current hydrological condition, it is reasonable to assume that the uranium mineralization in the Melawi region formed under a relatively undeformed paleogeographic setting. In addition, the paleochannels are expected to be present in the vicinity of the current river channel or within adjacent valley systems. Therefore, surface water features remain relevant indicators for interpreting historical fluid migration pathways.

A five-level buffer was applied to the river flow datasets and geological structure, ranging from 500 m to 2 km, to simulate zones of potential fluid migration and uranium transport along surface water pathways, faults, and fractures (see **Figure 4a-b**). The presence of porous

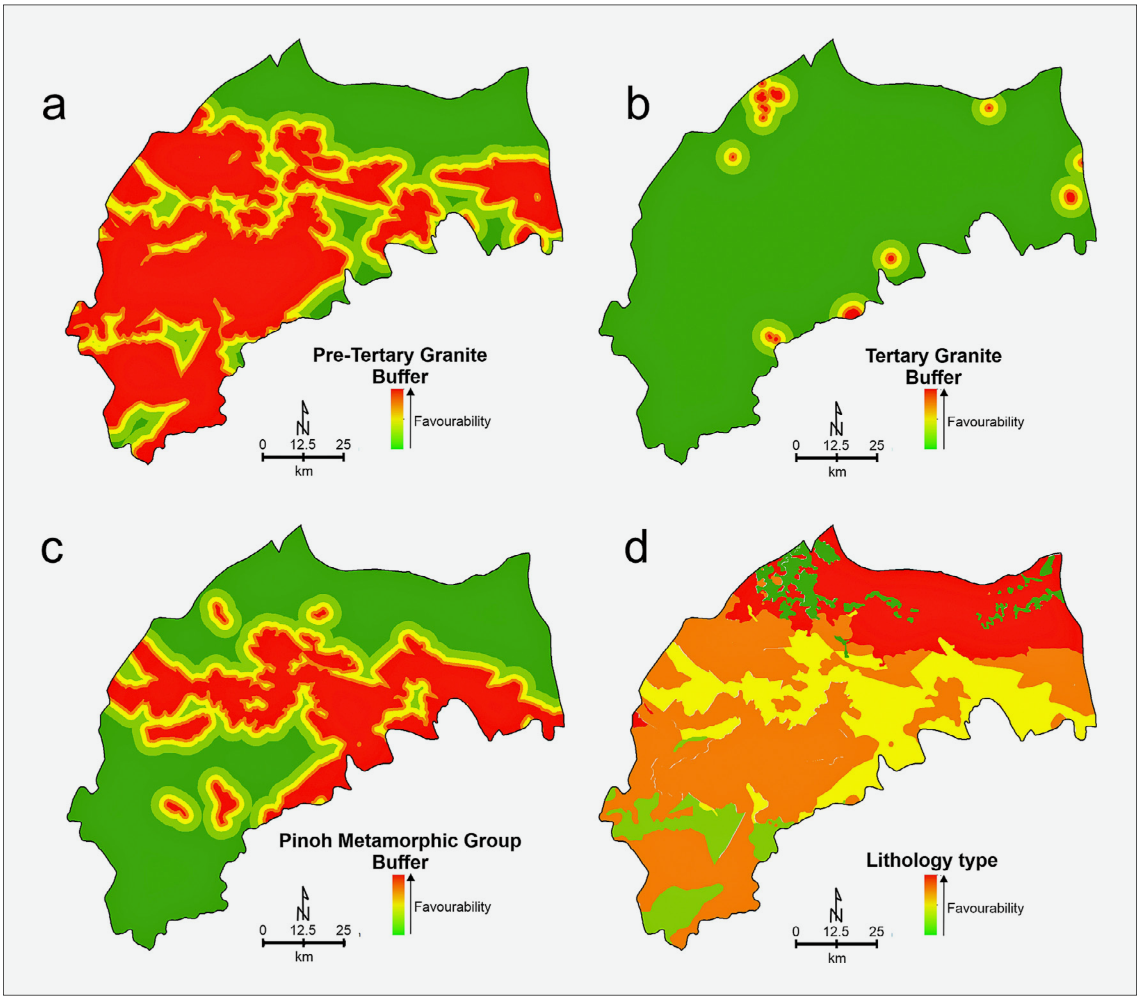

Figure 3. Predictor maps to generate the 'Source' map. (a) pre-tertiary granite, (b) tertiary granite, (c) Pinoh Metamorphic Group, and (d) lithology type.

and permeable media is another essential factor in facilitating uranium migration. These properties are typically reflected in sedimentary, volcanic, and alluvial lithologies in the Melawi region. The rock permeability map is classified into two categories: permeable and non-permeable rocks (see **Figure 4c**). Permeability values were assigned based on typical hydraulic conductivity ranges for unfractured rocks. Sandstones and pyroclastic rocks exhibit relatively high hydraulic conductivity, generally ranging from 10^{-10} to 10^{-4} m/s, with pyroclastic units reaching up to 10^{-6} m/s (**Zhang, 2013**). These lithologies were therefore classified as permeable. In contrast, granites and metamorphic rocks typically have much lower hydraulic conductivity values, ranging from 10^{-14} to 10^{-9} m/s (**Zhang, 2013**) and were accordingly classified as non-permeable. Although hydraulic conductivity can also be significantly influenced by fracturing, this effect is captured separately through the geological structure predictor map, which enhances favourability in areas where fracturing increases localized permeability.

To enhance the interpretation of surface water pathways and support paleochannel identification, a local topographic depression (local low) map is also generated (see **Figure 4d**). These depressions serve as natural catchments for surface runoff and are likely to align with former or existing flow paths. The local lows data were extracted from a digital elevation model (DEM) using 'Focal Statistics' tool within ArcGIS software. The resulting favourability classification for this map is binary (i.e. favourable or not favourable).

2.2.3. 'Trap' map

The potential of sandstone-type uranium deposits is interpreted based on the distribution of sandstone formation within the research area (see **Figure 5**). To assess this potential, sandstone formations are identified and grouped to delineate areas that provide a favorable geological environment for uranium accumulation. Based on regional geological maps, the sandstone formations contain significant amounts of organic material that could act as potential uranium traps. These formations include the Tebidah Formation, Payak Formation, Sekayam Sandstone, and Alat Sandstone. These formations serve as the primary host rocks in the genetic model of sandstone-type uranium deposits. The favourability of

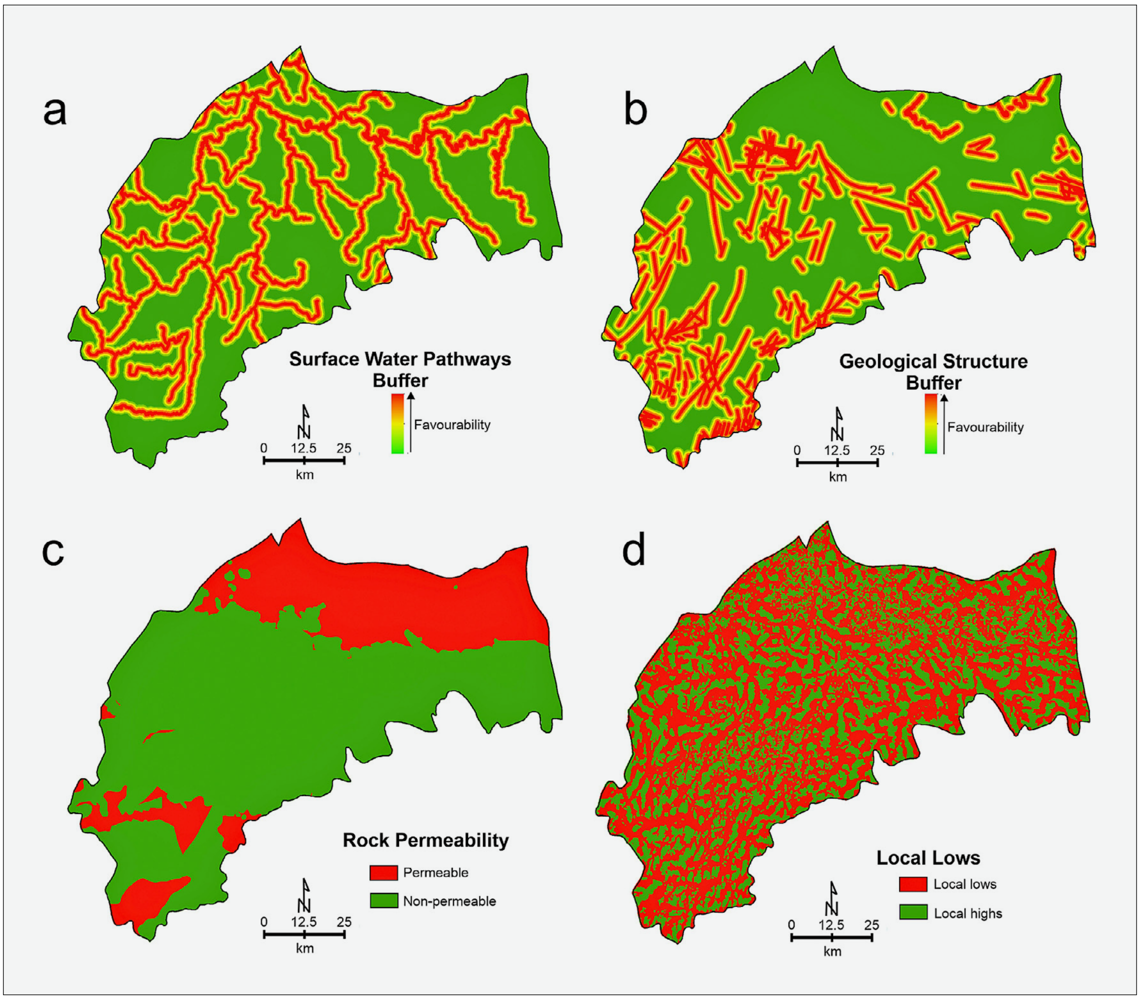

Figure 4. Predictor maps to generate the 'Transport' map. (a) surface water pathways, (b) geological structure, (c) rock permeability, and (d) local lows.

each unit was classified using a binary system ('yes' or 'no'), indicating whether the lithological conditions are conducive to uranium deposition. In addition, geomorphological features associated with groundwater and surface water movement are also considered in the analysis. Surface water pathways and topographic depressions (local lows) are integrated as potential trap components in the model. These features are critical for uranium deposition, as they influence fluid flow and create redox boundaries necessary for uranium precipitation. By incorporating these elements, the resulting prospectivity map provides a more comprehensive representation of the spatial conditions that control uranium accumulation in a sandstone-type system.

2.3. Fuzzy Value Scoring and Weighting

After compiling all predictor maps, a scoring and weighting procedure was applied to quantify the relative importance of each factor in the context of uranium mineralization model. Class scores were assigned on a 1–10 scale based on their geological favourability for uranium mineralization and each predictor map was then assigned a map weight, reflecting how strongly that parameter influences uranium sourcing, transport, or trap-

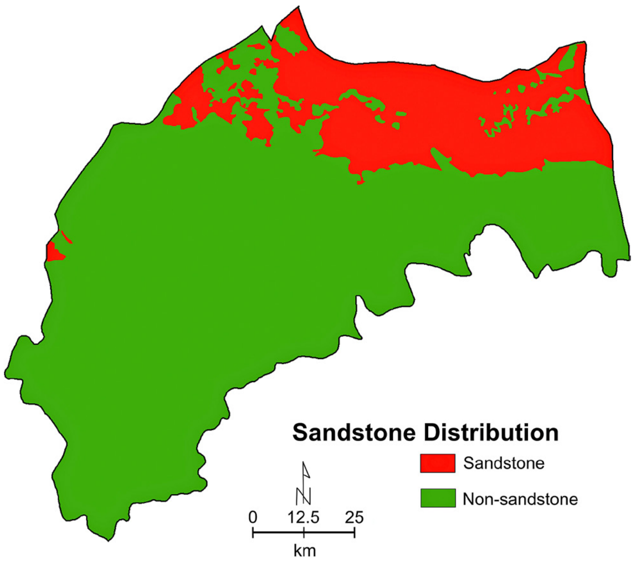

Figure 5. Sandstone distribution acts as a trap in fuzzy logic modelling.

Table 2. Justification of favourability for each parameter in fuzzy logic.

Maps			Favourability	Comment
'Source'	Granitoid Sources	Pre-tertiary granitoids	High	Older granitoids are more favorable due to prolonged weathering exposure. The older the rocks, the higher the favourability. The distance to the source also affect the favourability. The closer to the source, the higher the favorability
		Tertiary granitoids	Moderate - High	
	Metamorphic Sources		Moderate	Metamorphic rocks are generally unfavorable, but the Pinoh Metamorphic is an exception due to known uranium occurrences in the Kalan area. the closer to the source, the higher the favorability
	Lithology type		Moderate	All lithologies are considered to have a slight uranium potential.
'Transport'	Surface Water pathways		High	Plays a significant role in uranium mobilization. The closer to the water pathways, the higher the favourability.
	Geological structure		Low-Moderate	Creates subsurface flow and acts as a permeable medium. The closer to the structure, the higher the favourability.
	Local lows		Moderate	Serves as a natural catchment for surface runoff. Only local lows act as natural catchment.
	Rock permeability		Moderate - High	Functions as a permeable pathway for uranium transport. The more permeable the rocks, the more favourable as 'Transport' factor.
'Trap'	Surface Water pathways		Moderate - High	Reflects a paleochannel with potential as a uranium trap. The closer to the water pathways, the higher the favourability.
	Local lows		Moderate	Acts as a potential trap for uranium deposition
	Sandstone		High	Represents a major trap in sandstone-type uranium deposits

Table 3. Weighting of fuzzy values for each class in the generation of the 'Source' map.

Maps			Class	Class Score	Map Weight	Class Weight	Fuzzy Value
'Source'	Granitoid sources	Pre-tertiary granitoids	0.1 km	10	9	90	0.9
			1 km	9	9	81	0.81
			2.5 km	7	9	63	0.63
			5 km	5	9	45	0.45
			> 5 km	3	9	27	0.27
		Tertiary granitoids	0.1 km	10	7	70	0.7
			1 km	9	7	63	0.63
			2.5 km	7	7	49	0.49
			5 km	5	7	35	0.35
			> 5 km	3	7	21	0.21
	Metamorphic sources	Pinoh Metamorphic	0.1 km	10	5	50	0.5
			1 km	9	5	45	0.45
			2.5 km	7	5	35	0.35
			5 km	5	5	25	0.25
			> 5 km	3	5	15	0.15
	Lithology type		Intrusive	7	5	35	0.35
			Metamorphic	5	5	25	0.25
			Sedimentary	9	5	45	0.45
			Volcanic	3	5	15	0.15
			Alluvial	1	5	5	0.05

ping in the Melawi region, with the justification for each parameter and map weight summarized in **Table 2**.

To convert these inputs into fuzzy membership values, the scoring followed a two-step process. First, the class score was multiplied by the map weight to produce a class weight (class weight = class score × map weight). This value incorporates both the intrinsic favourability of each class and the relative significance of the parameter. Second, the class weight was divided by 100 to obtain the fuzzy membership value, resulting in standardized values between 0 and 1 that can be integrated within the fuzzy logic model.

Table 4. Weighting of fuzzy values for each class in the generation of the 'Transport' map.

Maps		Class	Class Score	Map Weight	Class Weight	Fuzzy Value
'Transport'	Surface water pathways	0,5 km	9	8	72	0.72
		1 km	7	8	56	0.56
		1.5 km	5	8	40	0.4
		2 km	3	8	24	0.24
		> 2 km	1	8	8	0.08
	Geological structure	0,5 km	9	4	36	0.36
		1 km	7	4	28	0.28
		1.5 km	5	4	20	0.2
		2 km	3	4	12	0.12
		> 2 km	1	4	4	0.04
	Local Lows	Local Low	9	5	45	0.45
		Local High	0	5	0	0.001
	Rock permeability	Permeable	9	7	63	0.63
		Non-Permeable	2	7	14	0.14

Table 5. Weighting of fuzzy values for each class in the generation of the 'Trap' map.

Maps		Class	Class Score	Map Weight	Class Weight	Fuzzy Value
'Trap'	Surface water pathways	0.5 km	9	7	63	0.63
		1 km	7	7	49	0.49
		1.5 km	5	7	35	0.35
		2 km	3	7	21	0.21
		> 2 km	1	7	7	0.07
	Local Lows	Local Low	9	5	45	0.45
		Local High	0	5	0	0.001
	Sandstone	Yes	9	9	81	0.81
		No	0	9	0	0.001

The assignment of class score and map weights was guided by three considerations: (1) the genetic model of sandstone-type uranium deposits, (2) geological evidence from Melawi, and (3) weighting references from **Bierlein & Bruce (2018)**. For example, pre-Tertiary granitoids received the highest weights in the 'Source' map because they are the most plausible uranium sources, while lithology types received lower weights due to their more indirect role. In the 'Transport' component, surface water pathways and rock permeability were weighted more heavily because they exert strong control on uranium mobility, whereas structures and local lows were weighted moderately. In the 'Trap' component, sandstone units received the highest weights as the main host for uranium precipitation, while local lows and surface water pathways were assigned moderate weights as secondary trapping indicators. The final class scores, map weights, class weights, and corresponding fuzzy membership values are presented in **Table 3 to Table 5**.

2.4. Prospectivity Map Generation

The predictor maps are integrated using fuzzy operators to generate the 'Source', 'Transport', and 'Trap' components, based on the process applied by **Bierlein & Bruce (2018) and Ciputra et al. (2019)**. This process culminates in the final prospectivity map for sandstone-type uranium deposits in the Melawi region, as illustrated in **Figure 6**. The fuzzy logic approach enables the combination of multiple spatial datasets with varying degrees of uncertainty and influence. In this analysis, the fuzzy operators employed include 'OR', 'SUM', and 'GAMMA', each selected based on its ability to represent specific relationships among the predictor variables. These operators facilitate the aggregation of input maps by capturing the cumulative favorability of multiple factors, thereby producing a continuous surface that reflects the spatial potential for uranium mineralization.

In constructing the 'Source' predictor map, proximity to uranium-bearing source rocks is the primary consideration. Buffer zones and weighting are applied to quantify the spatial influence of granitoid, metamorphic, and sedimentary units known or inferred to contain uranium. The overlay between multiple source types does not increase the favourability of the area to be a 'Source'. Therefore, the fuzzy 'OR' operator is employed to analyse the fuzzy values, as it selects the highest favourabil-

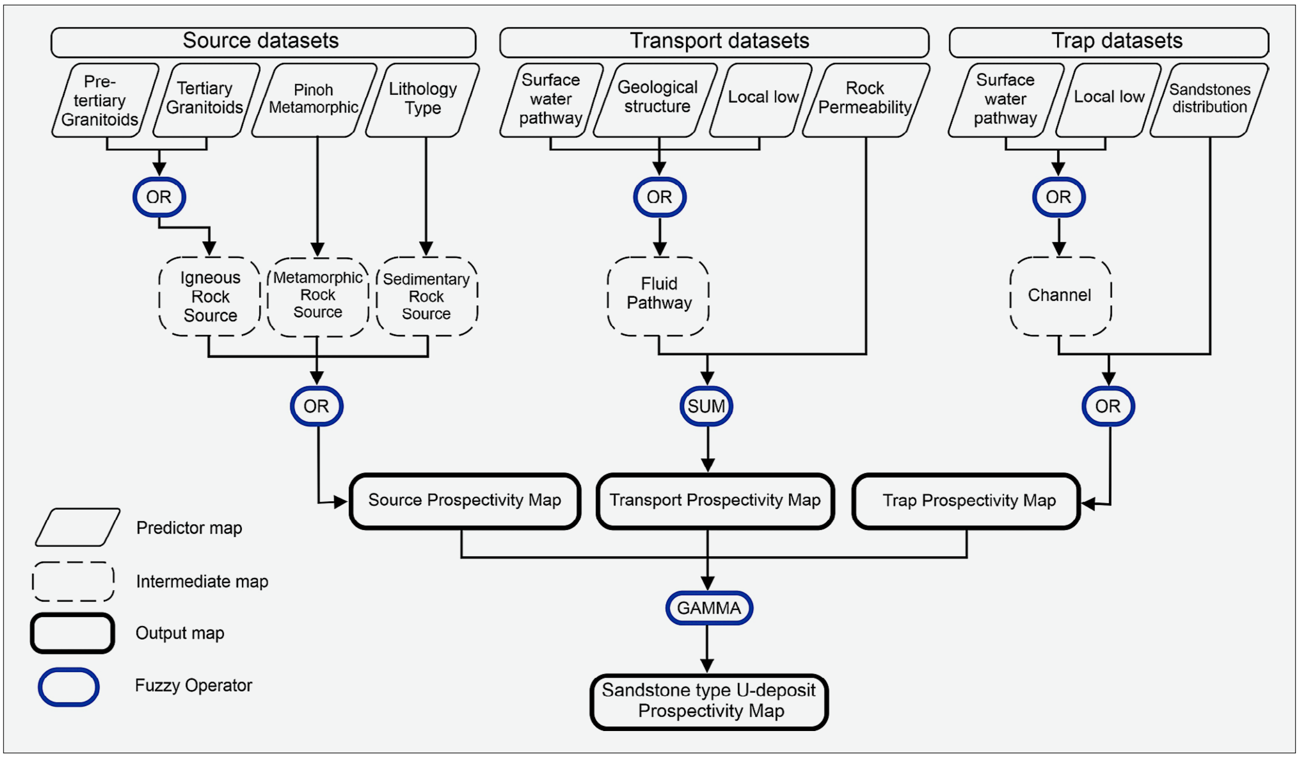

Figure 6. The fuzzy logic flowchart for generating a sandstone-type uranium deposit prospectivity map.

ity among overlapping layers. As a result, the final 'Source' map reflects the maximum favourability value from each of the contributing predictor maps, granitoid, metamorphic, and sedimentary rock units, rather than summing their individual effects.

For the 'Transport' map, a two-step fuzzy logic integration is applied. First, structural features, stream networks, and local lows are combined using the fuzzy 'OR' operator to create a composite 'Fluid Path' map, representing potential conduits for fluid movement. This layer is then merged with the rock permeability map using the fuzzy 'SUM' operator. The 'SUM' operator is chosen because both permeability and fluid pathways are mutually reinforcing factors in facilitating uranium transport. Their combined effect increases the overall favorability of the transport system.

The 'Trap' map is developed by identifying areas of potential uranium accumulation, primarily within sandstone-rich formations and channel-like features derived from surface hydrology and local lows. These predictor maps are integrated using the fuzzy 'OR' operator, as the presence of any one trapping mechanism is sufficient to suggest potential for uranium deposition.

In the final stage of analysis, the 'Source', 'Transport', and 'Trap' maps are integrated to generate the overall prospectivity map using the 'GAMMA' operator. This operator represents a compromise between the 'SUM' and 'PRODUCT' functions and requires the specification of gamma values. A low gamma input will produce an effect closer to 'PRODUCT' than 'SUM' and vice versa. In this study, a relatively low gamma value (gamma = 0.3) is applied to emphasize locations where all three components ('Source', 'Transport', and 'Trap') show high favourability. This approach ensures that areas with consistently high values across all three components are highlighted, while regions with lower favourability in one or more components still retain moderate potential depending on their composite fuzzy scores.

3. Results

The 'Source' favourability map for sandstone-type uranium mineralization (see **Figure 7a**) illustrates the potential of various lithological units to act as primary uranium sources. Zones of highest favourability, depicted in red, are prominently concentrated in the central and southern regions, spatially associated with the Menunuk Volcanic and the Sepauk Tonalite. These pre-Tertiary granitoid complexes are theoretically capable of contributing significant amounts of uranium to the mineralizing system. A secondary zone of moderately high favourability (shown in orange) is located in the western region, corresponding to the Sintang Intrusion, a Tertiary granitoid body also recognized for its uranium-bearing potential. Conversely, the northern segment of the area is characterized by low favourability (green), correlating with widespread sedimentary and metamorphic units of the Melawi region. These formations are generally considered to be geochemically depleted in uranium and thus less suitable as source rocks.

The 'Transport' favourability map (see **Figure 7b**) delineates zones that facilitate uranium mobilization

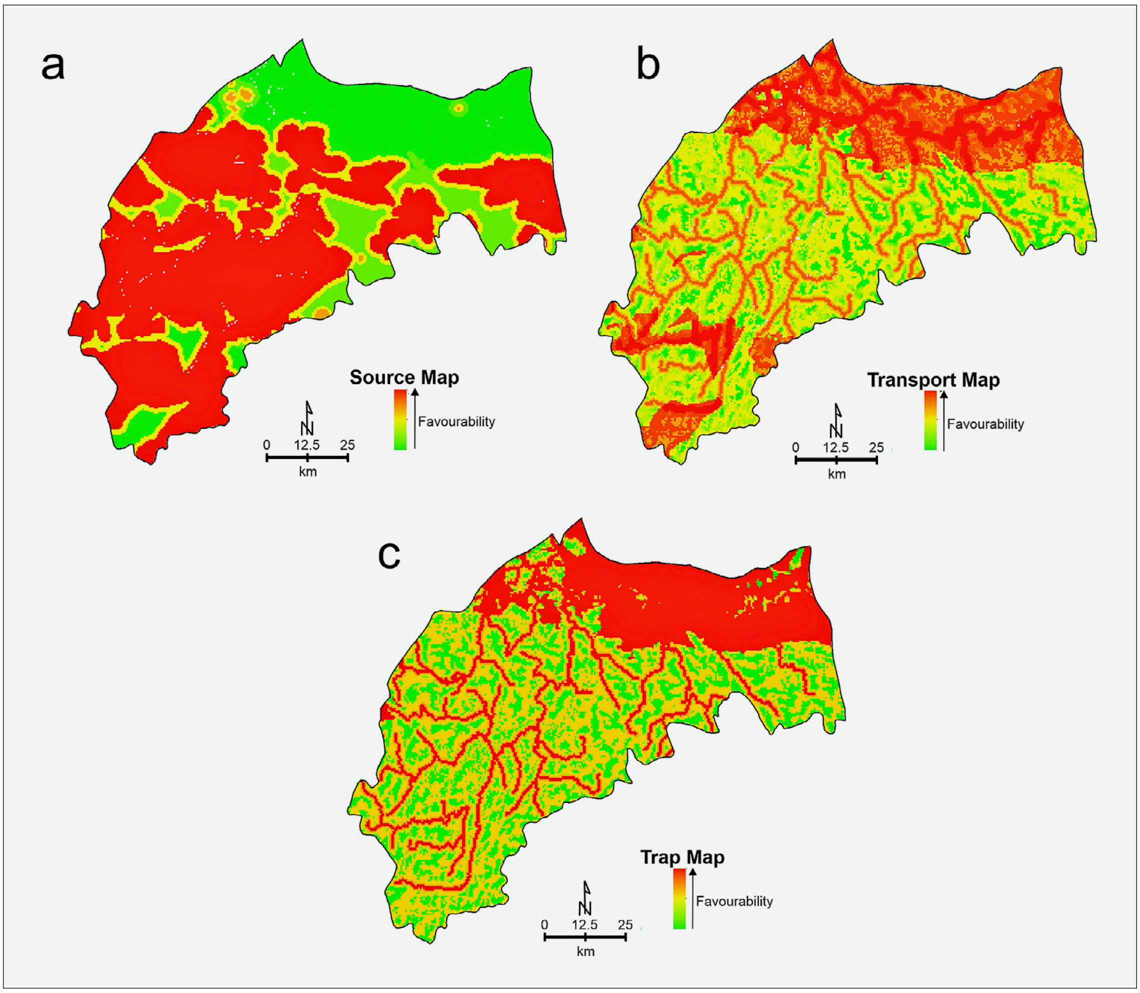

Figure 7. Favourability maps of (a) Source, (b) Transport, and (c) Trap for sandstone-type uranium deposit in Melawi.

through groundwater flow. Zones of high transport favourability are predominantly located in the northern and southwestern parts of the region, where steeper topographic gradients and dense drainage networks enhance subsurface fluid movement. These areas are underlain by permeable lithologies, including sandstones and pyroclastic volcanic deposits, which promote efficient uranium migration. Moderate favourability zones are dispersed across the central region, reflecting areas of partial hydrological connectivity and intermediate topographic slope. In contrast, low favourability zones are found in hydrologically isolated and topographically elevated areas, particularly in the southern part of Melawi, where limited permeability restricts fluid migration..

The 'Trap' favourability map (see **Figure 7c**) highlights zones with favorable conditions for the physical and geochemical retention of mobilized uranium. High trap favourability zones are concentrated in the northern region, corresponding to the Tebidah and Payak formations. These sedimentary units comprise interbedded sandstones with mudstones, siltstones, and subordinate coal seams, offering a combination of porosity, permeability, and redox interfaces ideal for uranium deposition. Additional high favourability zones are aligned with major surface water pathways, where topographic depressions and drainage convergence zones create localized trap environments. In contrast, the central and southern parts of the region exhibit low to moderate trap favourability. These regions are generally characterized by impermeable lithologies or elevated terrain, limiting their capacity to act as effective uranium traps.

The integrated prospectivity map for sandstone-hosted uranium deposits in the Melawi region, as illustrated in **Figure 8**, synthesizes the three critical components of the mineralizing system: source, transport, and trap. The highest prospectivity is concentrated in the northern part of the area, particularly where the Sepauk Tonalite is in direct contact with the Tebidah Formation, a geologically favorable interface for uranium mineralization. This area benefits from proximal source rocks, well-developed fluid transport pathways, and adequate sedimentary traps, representing approximately 36.64% of the total study area. Areas of moderate prospectivity, covering about 25.34%, are distributed along the regional drainage network and in topographic depressions, both of which act as potential zones for uranium pre-

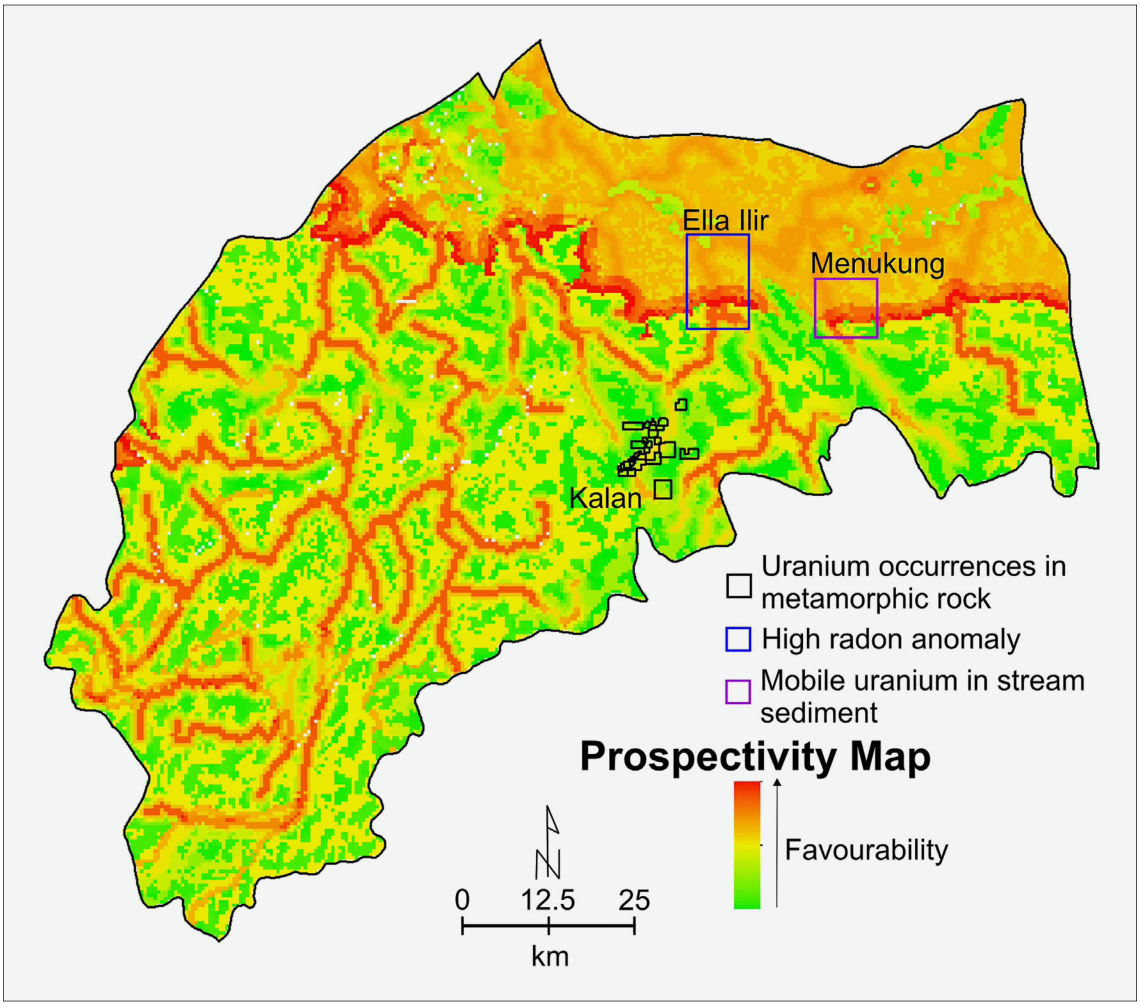

Figure 8. Prospectivity Map of sandstone-type uranium deposit in Melawi, West Kalimantan, Indonesia.

cipitation and concentration. In contrast, low prospectivity zones account for 38.02% of the area and correspond to areas lacking in one or more essential system components, typically those with inadequate source potential, limited permeability, or absence of trap mechanisms.

4. Discussion

The implementation of the source–transport–trap framework within a GIS-based fuzzy logic model provides a systematic and reproducible approach to assess uranium prospectivity in the Melawi region. By integrating geological, hydrological, and geomorphological data, the model enables spatially explicit assessments of favorability across diverse terrain. This discussion critically examines the extent to which the model outputs correspond with known regional geological features like lithological distributions, structural trends, and sedimentary environments. Additionally, the discussion identifies areas where the model may benefit from refinement, particularly in regions with limited data resolution, complex structural histories, or ambiguous geochemical signatures. These insights provide a foundation for improving predictive accuracy and guiding future field investigations.

4.1. Evaluation and validation of Prospectivity Mapping in the Melawi Region

The favourability of uranium source rocks in the Melawi region is closely associated with the occurrence of Pre-Tertiary granitoids, particularly the Sepauk Tonalite and Menunuk Volcanics. These felsic magmatic bodies are characteristically enriched in uranium and other incompatible elements (**Cuney, 2014**), suggesting that they represent the primary contributors to uranium supply in the regional system. The central and southern parts of the study area, where these granitoids are exposed, correspond to high favourability zones in the 'Source' fuzzy layer of the model. Geochemical analyses of granitoid rocks in West Kalimantan reveal variable uranium concentrations: 1.0–3.0 ppm U in Sepauk Tonalite, 0.3–3.7 ppm U in Menunuk Volcanics, and 4.0–7.48 ppm U in Sukadana Granite (**Breitfeld et al., 2020; Hennig et al., 2017**). In addition, metamorphic rocks in the Melawi region exhibit similar uranium concentrations, ranging from 0.3 to 3.8 ppm U (**Breitfeld et al., 2020**), could play a subsidiary role in sustaining long-term leaching and uranium release through weathering and fluid–rock interactions. Uranium concentrations in the Kalan area, specifically in the host rocks and associated weathered soils, range from 38.7 to 392.0 ppm U. While uranium concentration in the ore bodies has been reported to contain up to 2.8 wt.% U (**Adimedha et al., 2024**). These data suggest that both granitoid and metamorphic units in the region represent viable uranium sources, contributing to the overall mineralization system.

The configuration of slope gradients, drainage convergence, and permeable lithologies in the central-to-northern corridors of Melawi defines a coherent uranium transport pathway. This spatial pattern is consistent with the classical sandstone-type uranium system, in which oxidizing fluids leach uranium from felsic sources and migrate through porous host formations (**Bierlein & Bruce, 2018; IAEA, 2009**). The distribution of sandstones and fine-grained volcaniclastic rocks favours fluid infiltration and the maintenance of an oxidizing geochemical environment required for uranium transport. The topographic depressions and zones of drainage convergence identified in the fuzzy logic model coincide with possible uranium accumulation sites, consistent with known depositional settings where fluid velocity decreases and reductive conditions may dominate.

The Tebidah and Payak formations in the northern part of the Melawi region provide a particularly plausible trap environment. These formations exhibit favourable porosity and permeability conditions and contain interbedded mudstone and thin coal seams that serve as natural reductants (**Badaruddin et al., 2019**). The alternation between permeable and impermeable strata allows redox interfaces to develop within confined aquifer systems, analogous to those observed in well-documented sandstone-type uranium provinces such as the Wyoming basin and Ordos basin (**Hall et al., 2017; Jin et al., 2019**). The spatial proximity between the Tebidah–Payak sedimentary sequences and the granitoid bodies in the south further reinforces the geological plausibility of an integrated source–transport–trap mineralization system (**Cuney et al., 2022; Dahlkamp, 2009**).

The strong anomalous radon concentrations detected in the Ella Ilir area and the elevated mobile uranium in the Menukung stream sediments are consistent with this model, indicating active uranium mobility within the basin (**Cakrabuana et al., 2021b; Indrastomo et al., 2024**). Such patterns are typically associated with uranium-bearing fluids migrating from granitoid sources into reductive sandstone traps. The spatial alignment between these geochemical indicators and the modelled high-prospectivity zones suggests that the northern Melawi corridor may represent a dynamic interface between oxidizing and reducing regimes, where uranium could precipitate and accumulate. Overall, the geological configuration of the Melawi basin exhibits strong internal coherence with the source–transport–trap model, implying high geological plausibility for the occurrence of sandstone-type uranium mineralization.

4.2. Limitations and Improvements for Prospectivity Mapping in the Melawi Region

The prospectivity map generated for sandstone-type uranium mineralization in the Melawi region demonstrates the utility and flexibility of GIS-based fuzzy logic modeling. However, it also reveals certain limitations and assumptions that affect the precision and reliability of the analysis. A key issue lies in the input data quality and the assumptions embedded within the source–transport–trap model used in this study. In constructing the ‘Source’ favourability map, granitoid rocks were uniformly assumed to be uranium-bearing. While this generalization is useful for regional-scale mapping, it oversimplifies the geochemical variability inherent in granitic bodies. Not all granitoid rocks possess elevated uranium content; compositional differences linked to petrogenesis, tectonic setting, and magmatic evolution critically influence uranium enrichment potential. Incorporating the SIAM classification proposed by **Winter (2001)** and radiometric datasets (**Cakrabuana et al., 2021a; Sukadana et al., 2021**) would significantly improve model validity and discriminative capacity.

Similarly, the geological structure dataset used to represent the ‘Transport’ factor was derived from regional geological maps, which often include lineaments of ambiguous kinematic and temporal significance. In this study, all mapped structures were assumed to be open and capable of facilitating fluid migration. However, fluid pathways are governed by fracture aperture, connectivity, and orientation relative to stress fields (**Boadu, 2000**). Integrating high-resolution structural interpretations, fault kinematics, and fracture density from field-based or remote sensing analyses (e.g. InSAR, LiDAR) could significantly refine this model. The substitution of hydrogeological data with lithology-derived permeability assumptions is another simplification that affects the accuracy of the ‘Transport’ model. Actual groundwater flow conditions, governed by porosity, water table gradient, and recharge/discharge dynamics, are more complex and can significantly influence uranium mobility and localization. The inclusion of groundwater data, such as hydraulic conductivity and potentiometric surfaces, would offer a more realistic representation of the uranium migration pathway (**Bierlein & Bruce, 2018; Kreuzer et al., 2010**). Furthermore, the use of current surface water networks as proxies for paleochannels, although practical, introduces uncertainty. Paleochannels, which are often deeply buried, are key conduits and traps for uranium-bearing fluids in sandstone-type deposits (**IAEA, 2009**). Geophysical methods, along with sedimentological reconstructions, can help identify paleochannel features more accurately. Regarding the

'Trap' factor, the model correctly emphasizes the presence of Tebidah and Payak formations, both dominated by sandstones interbedded with mudstones and coal seams, as favourable lithologies for uranium precipitation. These units provide the reductive environment essential for sandstone-type uranium mineralization. However, incorporating redox interface mapping and detailed stratigraphic profiles would further constrain the trap potential of these units.

Despite these limitations, the fuzzy logic approach has shown strong potential in delineating prospective zones. Its ability to incorporate expert-driven weights and handle fuzzy boundaries between favourability classes is beneficial in areas with limited data resolution. The success of this approach in Melawi echoes its application in North Sumatra (**Ciputra et al., 2019b**), where high-favourability zones identified through fuzzy logic were validated through occurrences of uranium mineralization. Nevertheless, the outcomes of this study must be viewed as preliminary. To transition from broad regional modelling to exploration-ready targets, field validation is essential. High-resolution ground radiometric surveys, radon gas measurements, and stratigraphic test drilling should be prioritized in high-favourability zones to verify subsurface uranium concentrations and depth profiles. Subsequent petrographic and mineralogical analyses of core samples will provide valuable insight into uranium-hosting phases and alteration processes. Furthermore, continued integration of remote sensing, geophysics, and detailed geological mapping will enhance the predictive power of the model. Overall, the application of GIS-based fuzzy logic has proven effective in identifying sandstone-type uranium prospectivity in the Melawi region, but further refinement through advanced datasets and field-based confirmation will be crucial to advancing uranium exploration in this geologically promising area.

5. Conclusions

This study provides the first systematic regional-scale assessment of sandstone-type uranium prospectivity in the Melawi region, West Kalimantan, using an integrated GIS-based fuzzy logic approach. The results demonstrate that approximately 36.64% of the area exhibits high prospectivity, concentrated in the northern sector where the granitoid rocks are in direct contact with the sandstone formation, creating an interface that fulfills the essential 'source–transport–trap' criteria for uranium mineralization. These outcomes demonstrate the effectiveness of fuzzy logic in addressing geological uncertainty and limited dataset conditions that commonly challenge early-stage exploration in Indonesia. This finding also offers new insight into the spatial correlation between granitoid-derived uranium sources and sedimentary trap environments in Indonesia, highlighting Melawi as a geologically coherent and underexplored uranium deposit.

The prospectivity map produced in this study provides a prioritized uranium exploration area in Melawi region, West Kalimantan. This work advances uranium exploration research in Indonesia by establishing a replicable and transparent methodology that can be applied to other sedimentary basins across Indonesia. While the model successfully delineates key target zones, further refinement will require additional datasets and multidisciplinary validation. Integrating airborne radiometric surveys, hydrogeochemical sampling, fracture-density modelling, and paleochannel reconstruction would significantly enhance predictive confidence. Overall, this study establishes a new benchmark for regional uranium prospectivity modelling in Indonesia, providing both scientific insight and practical guidance to support the development of domestic uranium resources for sustainable energy security.

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SAŽETAK

Primjena geografskoga informacijskog sustava za istraživanje ležišta uranija pješčenjačkoga tipa u regiji Melawi, Zapadni Kalimantan, Indonezija

Regija Melawi u Indoneziji identificirana je kao metamorfno ležište uranija. Pojava sedimentnih formacija u nizvodnome području upućuje na potencijal za ležišta uranija pješčenjačkoga tipa. Prethodne studije usredotočile su se na metamorfnu mineralizaciju, što je rezultiralo ograničenim istraživanjem sedimentnih stijena. Tehnologija geografskoga informacijskog sustava (GIS) nudi vrijednu podršku za analizu mineralne perspektive, uključujući istraživanje uranija. Među raznim tehnikama pokazalo se da je *fuzzy* logika učinkovita u generiranju karata perspektivnosti za usmjeravanje razvoja resursa uranija. Cilj je ovoga istraživanja razvoj karte perspektivnosti za ležište uranija pješčenjačkoga tipa u regiji Melawi. Analiza temeljena na GIS-u provedena je korištenjem dostupnih prostornih skupova podataka, uključujući geološke karte, digitalne modele reljefa i pojave uranija u Melawiju. Ovi skupovi podataka poslužili su kao ulaz za izradu *fuzzy* logičkoga modela temeljenoga na genetskome modelu ležišta uranija pješčenjačkoga tipa. Skupovi podataka reklasificirani su, dodijeljeni su im bodovi prikladnosti i obrađeni su unutar okvira *fuzzy* logike za generiranje karte perspektivnosti. Rezultati pokazuju da je 36,64 % područja Melawi zona visoke perspektivnosti, 25,34 % zona srednje perspektivnosti, a 38,02 % zona niske perspektivnosti. Sjeverni dio Melawija pokazuje najpovoljnije uvjete za mineralizaciju uranija u pješčenjaku. Ova studija demonstrira *fuzzy* logiku kao praktičan alat za određivanje povoljnoga područja ležišta uranija pješčenjačkoga tipa u Melawiju. Ipak, za točno lociranje ležišta uranija potrebno je uključivanje raznolikijih prostornih skupova podataka i provedba sustavne terenske validacije.

Ključne riječi:
Melawi, GIS, *fuzzy* logika, mineralna perspektiva, uran pješčenjačkoga tipa

Author's contribution

Tyto Baskara Adimedha (Researcher, Geology): conceptualization, methodology, formal analysis, writing-original draft, and visualization. **Roni Cahya Ciputra** (Researcher, Geology): methodology, formal analysis, writing-original draft, and visualization. **Frederikus Dian Indrastomo** (Researcher, Geology): resources, validation, writing – review and editing. **I Gde Sukadana** (Doctor, Geology): methodology, resources, validation, writing – review and editing. **Heri Syaeful** (Doctor, Geology): conceptualization, methodology, supervision, writing – review and editing. **Yoshi Rachael** (Researcher, Geology): formal analysis, writing – review and editing.
All authors have read and agreed to the published version of the manuscript.